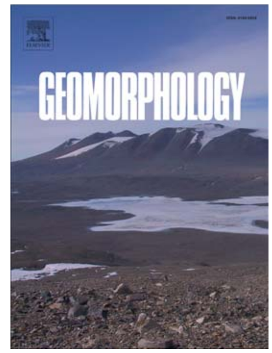

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Scale-dependent behavior of the foredune: Implications for barrier island response to storms and sea-level rise

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Abstract

The impact of storm surge on a barrier island tends to be considered from a single cross-shore dimension, dependent on the relative elevations of the storm surge and dune crest. However, the foredune is rarely uniform and can exhibit considerable variation in height and width at a range of length scales. In this study, LiDAR data from barrier islands in Texas and Florida are used to explore how shoreline position and dune morphology vary alongshore, and to determine how this variability is altered or reinforced by storms and post-storm recovery. Wavelet analysis reveals that a power law can approximate historical shoreline change across all scales, but that storm-scale shoreline change (~10 years) and dune height exhibit similar scale-dependent variations at swash and surf zone scales (<1000 m). The in-phase nature of the relationship between dune height and storm-scale shoreline change indicates that areas of greater storm-scale shoreline retreat are associated with areas of smaller dunes. It is argued that the decoupling of storm-scale and historical shoreline change at swash and surf zone scales is also associated with the alongshore redistribution of sediment and the tendency of shorelines to evolve to a more diffusive (or straight) pattern with time. The wavelet analysis of the data for post-storm dune recovery is also characterized by red noise at the smallest scales characteristic of diffusive systems, suggesting that it is possible that small-scale variations in dune height can be repaired through alongshore recovery and expansion if there is sufficient time between storms. However, the time required for dune recovery exceeds the time between storms capable of eroding and overwashing the dune. Correlation between historical shoreline retreat and the variance of the dune at swash and surf zone scales suggests that the persistence of the dune is an important control on transgression through island migration or shoreline retreat with relative sea-level rise.

Keywords: barrier island, foredune, shoreline change, recovery

Introduction

The vulnerability of a barrier island to extreme storms depends on the elevation of the total water level (tide+storm surge+wave run-up) relative to the height and volume of the foredune (Thieler and Young, 1991; Sallenger, 2000; Morton, 2002; Houser and Hamilton, 2009). Storms can have a range of visible impacts, from minor scarping at the base of the dune to overwash and/or breaching when dune heights are relatively small compared to the storm surge (Sallenger, 2000; Hesp, 2002). Depending on the regional sediment supply, sea-level rise may lead to island transgression through either landward migration or shoreline retreat during storms capable of overtopping or breaching the dunes, thus transporting sediment to the back-barrier shoreline in the form of washover fans and terraces. The threshold surge required for the dunes to be overtopped or breached decreases as sea level rises, and the probability of island overwash and island transgression increases. A lower washover threshold also develops where dunes lack height (Sallenger, 2000), creating the potential for rapid transgression and even overstepping of relatively low islands. For an island to transgress and remain a subaerial landform requires that the island can move landward and remain above sea level through the redistribution of sediment through washover from the seaward side of the island to the back-barrier shoreline.

A simple two-dimensional model of storm impact is overly simplistic and does not explicitly recognize alongshore variability in dune height and volume at a range of scales (Walker et al., 2017). At the largest spatial scales, alongshore variability in dune height is a result of island transgression over a framework geology of irregularly preserved stratigraphic units of variable ages, composition and geometries and/or sedimentary features offshore. The variable framework geology alters the local bathymetry, sediment supply, and sediment texture, which combined alter the supply and transport of sediment amongst the nearshore, beach and dune (see McNinch, 2004; Houser, 2009, 2012; Hapke et al., 2010; Houser and Mathew, 2011; Lentz and Hapke, 2011). At smaller scales, dune variability can develop in response to swash and surf zone scale (<1000 m) variations in storm surge (e.g. Stockdon et al., 2007) or anthropogenic forcing (e.g. Smith et al., 2008; Kratzmnn and Hapke, 2010; Lentz et al., 2011; Houser et al., 2012; Jewell et al., 2014; Elko et al., 2016). Because the washover threshold is lower for those areas where the dune height and/or volume is lower, gaps in the dunes are reinforced during each storm (see Weymer et al., 2015), and potentially expanded through lateral erosion of adjacent dunes (see Houser and Hamilton, 2009; Houser, 2013). An increase in the frequency and/or magnitude of storm surge has the potential to promote burial-tolerant species and the development of low dunes and a new equilibrium state (Stallins and Parker, 2003; Duran and Moore, 2013; Wolner et al., 2013). However, given sufficient time between storms, it is possible for dune-building vegetation to recolonize the beach, and for sediment to be delivered to the beach from alongshore or offshore sources (e.g. Hequette and Ruz, 1991; Psuty, 1992; Schwab et al., 2000; Hansom, 2001; Houser et al., 2008). In this respect, the rate of island transgression depends on the probability and realized sequencing of storm surge events relative to the average height and variability of the foredune alongshore across a range of spatial scales (see Sallenger, 2000; Masetti et al., 2008). As shown by Duran and Moore (2015), rapid sea-level rise has the potential to cause islands to become trapped in a low-elevation state that is susceptible to erosion and washover during relatively small storms.

Quantifying the scales at which shoreline change and dune morphology vary alongshore is an essential step to understanding the physical processes controlling beach and dune morphology, and the evolution of barrier islands in response to storms and sea-level rise. Recent work by Tebbens et al. (2002) and Lazarus et al. (2011) showed that shoreline change (the trend in shoreline location through time) along the Outer Banks follows a power law alongshore, which suggests that a single process may dominate across scales from small scale swash zone processes (<100 m) to the scales typically associated with variations in the framework geology and island curvature (> 1000 m). In other words, shoreline change appears to be scale invariant (see Bak, 1996; Murray, 2007), despite different processes and feedbacks operating at swash, surf zone, shoreface and island scales (see Lazarus et al., 2011). The scale invariant nature of shoreline change is due to the development of alongshore transport gradients that dissipate small-scale variations in the shoreline, and the dominance of large-scale gradients resulting from island curvature or a dominant framework geology (see Stone et al., 1992). While historical shoreline change has been shown to be scale independent, the persistent alongshore variation of dune height on many barrier islands suggests that dune morphology may exhibit a scale-dependent behavior associated with the framework geology. This is consistent with recent field and modeling studies that demonstrate how gaps in the dune are maintained/reinforced through lateral erosion by washover (Houser, 2013; Weymer et al., 2015; Goldstein and Moore, 2017), and blowouts (Jewell et al., 2014). Since washover affects longshore transport gradients through the redistribution of sediment, it is reasonable to expect that storm-scale and historical rates of shoreline retreat depend (to varying degrees) on the alongshore variability of dune height, once established. It is important to note that the relationship between dune height variability and shoreline retreat is not unidirectional as shoreline retreat from a lack of sediment supply or frequent storms limits the ability of the dune to recover, which leads to increased washover and a maintenance of the variability (see Houser, 2013; Duran and Moore, 2013; Wolner et al., 2016).

The purpose of this study is to quantify the alongshore scaling of dune height and where possible dune height recovery at several barrier islands from Texas, Florida and Maryland in relation to storm-scale (<10 year) and historical (~100 year) shoreline change. It is important to note that the focus of this study is not on the differences in dune height and morphology between islands in response to variations in sediment supply and transport amongst nearshore, beach and dune (see Hesp, 2002; Walker et al., 2017). Rather, the focus of this study is to determine how dune height and morphology vary across multiple spatial and temporal scales on islands that have been the focus of several beach-dune interaction studies by the authors.

Study Sites

The analysis for this study was completed at Gulf Islands (GI), North Padre Island (PN), South Padre Island (PS), Matagorda Peninsula (MP) and Folletts Island (FO) (Fig. 1). These islands were selected based on the availability of data, and *a priori* knowledge by the authors of whether the islands have a variable framework geology. Additional data from Assateague Island (AI), from Hammond (2015), was used to examine the relationship between dune variability and alongshore average historical island retreat. The lack of adequate spatial series for storm-scale and historical shoreline retreat restricted the use of AI for most of the analyses. The alongshore variation in dune height for all island is presented in Fig. 2.

Gulf Islands, Florida (GI)

The Gulf Islands is a narrow sandy barrier island extending 96 km from East Pass near Destin to Pensacola Pass in the west. The focus of this study is a 35 km stretch of Gulf Islands in northwest Florida that was impacted by hurricanes Ivan (2004), Dennis (2005) and Katrina (2005). This area has also been the focus of numerous previous studies of storm response and recovery within the Gulf Islands National Seashore (e.g. Houser et al., 2008; Houser and Hamilton, 2009; Claudino-Sales et al., 2010). The island is fronted by a ridge and swale bathymetry that creates a coincident variation in beach and dune morphology ranging from transverse bar and rip morphology and small discontinuous dunes landward of the swales to longshore-bar and trough with relatively large dunes landward of the offshore ridges. A geological survey by Houser (2012) supported an earlier theory presented in Houser et al. (2008) that the ridge and swale topography may be a transgressive surface that developed in as the island migrated landward with relative sea level rise. In this respect, the variation in beach and dune morphology is expected to exhibit a strong dependency on the framework geology.

North Padre Island, Texas (PN)

Padre Island is characterized by a relatively dissipative profile with multiple bars offshore and a wide low-angled beach profile. Geologic surveys suggest that Padre Island developed either from offshore shoals and spit accretion or from sediment migrating from older beach ridges submerged by rising sea level (Brown et al., 1977; Fisk, 1959; Weise and White, 1980). As sea level stabilized toward the present-day, a chain of short barrier islands along the Texas coast developed between the divides of older Pleistocene river valleys, and the short barriers accreted into larger barriers that compose the modern Texas coastline through alongshore drift (Fisk, 1959). In this respect, shoreline change, and beach and dune morphology at Padre Island is influenced by the framework geology, but not with the alongshore regularity observed at GI. Driving is permitted on PN and has been shown to lower the elevation of the dune crest through a reduction in the elevation of the beach and backshore elevation. The lower elevation of the dune base and crest makes the dunes driving section susceptible to scarping and overwash during storms (Houser et al., 2012), which in turn increases the amount of sediment transported landward of the dune through washover or blowouts (Jewell et al., 2014).

South Padre Island, Texas (PS)

South Padre Island is the southernmost part of a large arcuate system of barrier islands and spits that extends approximately 600 km from the Bolivar Peninsula at the mouth of Galveston Bay. Sediment to the barrier is largely supplied by sediment from the Rio Grande River Delta to the south, but reductions in the flow of the Rio Grande and reservoir sedimentation have led to a substantial loss of sediment supply (Morton and Pieper, 1975; Mathewson and Minter, 1976). Consequently, the island has been experiencing widespread erosion, particularly during hurricanes capable of breaching the dunes and moving sediment into Laguna Madre through washover channels (Shideler and Smith, 1984). As described by Houser and Mathew (2013), variations in beach and dune morphology appear to be directly forced by wave refraction over the inner-shelf bathymetry. The phase relationship between the offshore ridges and the inshore wave height at all length scales suggests that the waves are refracted and focused immediately south of where the foreshore slope is at a local minimum. The inshore wave height reaches a local minimum south of areas with a steeper foreshore slope and in the lee of the northeast-trending ridges. While the framework geology is similar to GI, the largest dunes are found landward of the swales on PS. The opposite behaviors of GI and PS is a result of the more dissipative beach and nearshore morphology of southern Texas. Similar to PN, driving is permitted along the entire length of PS, but the island is not as popular or accessible as PN and the impact of driving has not been examined.

Matagorda Peninsula, Texas (MP)

Matagorda Peninsula is a low-lying and narrow transgressive barrier spit that separates Matagorda Bay from the Gulf of Mexico along the northeast coast of Texas (Wilkinson and Basse, 1977). McGowen and Brewton (1975) describe the barrier as being in an erosional state as a result of a deficit of sediment from alongshore, in addition to human activities such as the construction of dams on the Brazos and Colorado Rivers that limited sediment supply. The rate of erosion is estimated to be ~ 1 m yr^{-1} based on the change in shoreline position between 1855 and 1974 (Morton, 1977). Wilkinson and McGowen (1977) argue that the modern rate of recession is up to 30 to 40% greater than the historical (defined by the authors as "pre-historic") average assumed over the Holocene. Rates of erosion are, however, quite variable along the length of Matagorda Peninsula, and range from 1 m yr^{-1} at the Colorado River navigation channel to 0.5 m of accretion ~ 15 km to the north of the channel. At the northern terminus, rates of erosion are ~ 4 m yr^{-1} (Gibeaut et al., 2000). The erosion is not continuous but occurs episodically in response to extreme storms (Morton, 1979). Matagorda Peninsula was in the right front quadrant of Hurricane Carla (1961) with a storm surge of ~ 3 m over the Matagorda Peninsula that resulted in 32 breaches (Morton, 1979) with an average spacing of ~ 870 m. Shoreline retreat during this single storm is estimated to be ~ 250 m (McGowen and Scott, 1975). There are no known framework geology controls on the morphology of Matagorda Peninsula.

Follets Island, Texas (FO)

Follets Island is a relatively small (~20 km long), narrow transgressive barrier island that extends northeast from Freeport, Texas. The island is separated from Galveston Island to the north by San Louis Pass, which is periodically dredged to maintain connectivity between Christmas Bay and the Gulf of Mexico. Residential and commercial development is primarily concentrated in the southern third of the island, although sparse residential development does extend the entire length of the island. Follets Island is a very low-lying island with a maximum island elevation of approximately 2 m. Dunes have been repeatedly breached by hurricanes, as is evident in historical air photos. Repeat washover of sediment from the Gulf of Mexico shoreline to the back-barrier shoreline has resulted in extensive washover fans extending into Christmas Bay. Additional erosional features on the island include significant scours along the beach, resembling the scours identified along the Bolivar Peninsula due to concentrated offshore (ebb) flow following Hurricane Ike (Sherman et al., 2013).

Assateague Island (AI)

Assateague Island is located along the mid-Atlantic coast of the eastern United States, between Ocean City, Maryland to the north, and Chincoteague, Virginia, to the south. The island is ~60 km long and varies in width from ~220 m at its northern end to ~4.5 km near Chincoteague. The island is generally low lying, with a mean elevation of 0.9 m, with the highest elevations toward the southern end of the island. A jetty built updrift in Ocean City, MD has created a limited availability of sediment from alongshore and a rapid transgression of the northern part of the island (Leatherman 1976), at a rate ranging from 11 m yr^{-1} to 12.2 m yr^{-1} (Thornberry-Ehrlich, 2005). Large storms have overwashed portions of Assateague Island episodically, leading to dune erosion and in some cases creating temporary inlets (Truitt, 1968; Krantz et al., 2009). Recent storms including Nor'Ida, Hurricane Irene, Hurricane Sandy and Winter Storm Jonas generated large storm surges and wave run-up leading to overwash at several locations on the island. Storm washover is promoted through ability for visitors to Assateague Island National Seashore to drive on the beach. Driving on the beach at AI immediately following a storm has been shown to limit the ability of dune vegetation to colonize the backshore, which limits the amount of sediment trapped by vegetation and required for foredune recovery at the pre-storm position of the dune (Houser et al., 2012).

Methods

The source of the data used to quantify the alongshore variation in dune height and shoreline change is provided in Table 1. For all islands, high-resolution digital elevation models (DEMs) were produced for each island from airborne LiDAR (light detection and ranging) surveys completed by the United States Geological Survey (USGS), the National Park Service (NPS) or local government organizations (e.g. Escambia County, Florida). LiDAR involves the collection of spatially dense and accurate topographic data using aircraft-mounted lasers capable of recording elevation measurements with a vertical accuracy of up to 0.15 m, and a horizontal accuracy of ~1 m. The Gulf Islands dataset (from May 2004) is a product of the USACE and Optech Inc., which is more commonly known as the Compact Hydrographic Airborne Rapid Total Survey (CHARTS). This system is a combination of a 1000 Hz hydrographic sensor, a 10,000 Hz topographic sensor, and an image sensor. The surveys for the barrier islands in Texas were also completed using CHARTS. For all islands, the data are acquired from a single continuous flight and do not include data from multiple flights to avoid any confounding influence of seasonality.

Post-processed ASCII data sets with *x, y, z,* and intensity values corresponding to last return were used for all islands examined. Airborne LiDAR surveys produce a cloud of points with irregular spacing. The point clouds were exported as ESRI shape files for later use and to match all tiles together in a map file and converted to a DEM. Point elevation data were interpolated into binary raster grids with 1-m cell size using the inverse distance weighted (IDW) algorithm method for each tile with a search radius of 10 m consistent with the methods used in the associated studies completed by the authors on the same islands (Houser et al., 2008; 2015;

Houser and Mathew, 2011 Houser, 2013; Jewell et al., 2014; Hammond, 2015). The DEMs have horizontal and vertical accuracies of ~1.0 m and 0.15 m, respectively, as determined by randomly distributed points withheld from the original point cloud when producing the DEM. The cross-shore variation in beach-dune morphology was extracted along transects perpendicular to the shoreline at 50 m intervals alongshore. The elevation was interpolated along each transect at 1-m intervals from mean sea level ($x = 0$) to either 200 m inland from the shoreline (Gulf Islands) or 700 m from the shoreline (Padre Island).

For all islands, dune heights were extracted from the DEMs using the automated relative relief method described by Wernette et al. (2016). Relative relief (RR) is an indicator of a pixel's topographic position, which makes it very useful in identifying morphologic features that include topographic position in their semantic definition, including dune toe, dune crest, and dune heel. Relative relief is calculated as:

$$RR_i = \frac{(z_i - z_{min})}{(z_{max} - z_{min})} \quad (1)$$

where RR_i is the relative relief at pixel i, Z_i is the elevation at pixel i, Z_{min} is the minimum elevation within the specified window, and Z_{max} is the maximum elevation within the specified window. In other words, this metric is a measure of topographic position ranging from 0 (local topographic bottom) to 1 (local topographic top) within a given area (*i.e.* computational window). Features are extracted by comparing the elevation or average RR value across 21, 23, and 25 m computational windows to a threshold that is based on the semantic definition of the landscape feature and the histogram of calculated RR value. The RR threshold for the dune toe and crest is based on the histogram of calculated average RR values, while dune crest is conceptually the inverse of the dune toe. The dune height is calculated by subtracting the dune toe elevation from the dune crest elevation. As described by Wernette et al. (2016), the RR approach out-performs contemporary approaches involving inflection or least-cost path analysis (see Stockdon et al., 2007, 2009; Mitasova et al., 2009, 2011), and does not require that the dune toe, crest, or heel are spatially continuous, which is important because dune morphology is likely naturally variable alongshore. A noted, the alongshore variation in dune height for all islands is presented in Fig. 2.

Following the methods used in Houser et al. (2008), shoreline change was examined at two different timescales (storm and historical) using the Digital Shoreline Analysis System (DSAS; Theiler et al., 2008), producing rates of shoreline change on shore-perpendicular transects spaced at 50 m intervals. The historical shoreline change rates used for this analysis are derived from both historical maps and recent LiDAR data. For all islands, historical shorelines were digitized from georeferenced NOS T-sheets, and represent the field interpretation of a high-water line (HWL) on the beach (see Shalowitz, 1964). The modern shorelines are mean high water (MHW) shorelines derived from previously published studies involving LiDAR data based on elevation contours (Houser et al., 2008; Wernette et al., 2016), with the most recent endpoint being the LiDAR data used to characterize the alongshore variation of the dunes. The historical and storm-scale change rates for Gulf Islands are derived from Houser et al. (2008). Historical and recent shoreline change data for all barrier islands in Texas was obtained from the Texas Shoreline Change Project (http://www.beg.utexas.edu/coastal/tscp.php; see Wernette et al., 2016). In all cases, shoreline change was calculated for the entire length of the island at regular intervals to create an alongshore series for further analysis.

The extracted island metrics were decomposed using a continuous wavelet transformation (CWT) with a complex Morlet wavelet. First introduced by Grossman and Morlet (1985), wavelet analysis allows for a signal to be evaluated for amplitude and phase at each spectral component locally within the signal (Torrence and Compo, 1998). In other words, a wavelet decomposes and localizes the variability of a spatial series in both frequency (scale) and time domains simultaneously. This leaves the higher frequency components of the signal intact, allowing for a high-resolution evaluation of the signal. This technique overcomes shortcomings with other analysis methods, including Fourier analysis, which only allows the overall strength of the signal to be evaluated at certain pre-determined frequencies. In this respect, wavelets serve as a valuable approach to extract detailed information about the spatial structure of the dune and shoreline along the entire length of all islands examined in this study.

The wavelet transform is a convolution of a sequence xn, where n = 0… N – 1, with a translated and scaled version of a normalized wavelet function φ0 (η):

$$W_n^x(s) = \sum_{n=0}^{N-1} x_n \psi^* \left[\frac{(n' - n)dx}{s}\right] \tag{2}$$

where (*) indicates the complex conjugate, dx is the time step, N is the number of points in the time series, and s is the width of the wavelet scale (also known as the dilution function). The Morlet wavelet is used in this study because the temporal and frequency domains can localize characteristics of the data set well (Torrance and Compo, 1998) and have been used successfully in previous research on nearshore bars (e.g. Li et al., 2005; Ruessink et al., 2006; Castelle et al., 2007; 2010), and barrier behavior in response to the ENSO teleconnection (Clarke et al., 2017). The Morlet wavelet is defined as:

$$\psi_o(\eta) = \pi^{-\frac{1}{4}} e^{i\omega_o \eta} e^{-\frac{1}{2\eta^2}} \tag{3}$$

where η is the non-dimensional time parameter and ω0 is the non-dimensional frequency (is 6 for the Morlet wavelet). A non-orthogonal wavelet function is used for the continuous wavelet transform (Farge, 1992) instead of the discrete wavelet transform because it is better equipped to extract features from the signal.

To aid in the interpretation of the wavelet data, Global Wavelets (GW) were subsequently extracted from the cross-wavelet transformation (CWT) using AutoSignal©, signal processing software. Specifically, the GW spectrum ($\overline{W}_n^2(s)$) is the sum of all local wavelet spectra:

$$\overline{W}_n^2(s) = \frac{1}{n}\sum_{n=0}^{n-1}|W_n(s)| \tag{4}$$

which represent the power spectrum of a time series with an impartial and consistent estimation. The global wavelet spectrum allows dominant frequencies in the data series to be emphasized. Plotting the computed GW variance against the alongshore scales (*i.e.* wavelength) provides useful information about the spatial structure of the alongshore data. A white noise GW (λ^0) suggests that local (or small-scale) scale-dependent variations dominate relative to larger-scale variations alongshore. Pink noise ($\lambda^{\sim 1}$) is associated with variations that are structurally controlled or reinforced (ie. scale-dependent), while red noise ($\lambda^{\sim 2}$) is associated with diffusive transport processes in which small-scale variability is limited and the variation is scale-independent. As described by Lazarus et al. (2011), historical shoreline change from the Outer Banks of North Carolina exhibits a red noise spectrum suggesting that change at scales associated with island curvature (>1000 m) is responsible for the greatest amount of shoreline change. The scale invariant nature of shoreline change is due to the development of alongshore transport gradients resulting from island curvature that dissipate small-scale variations in the shoreline unless there is a dominant framework geology. The islands in the present study have lengths of up to 10 km, and following definitions provided by Lazarus et al. (2011), the variation in dune height and shoreline change is examined at scales associated with swash (<100 m) and surf (<1000 m) zone processes, and island curvature or framework geology (<10,000 m).

Results

Gulf Islands, Florida

On Gulf Islands (GI), there is a considerable variation in dune morphology ranging from an absence of dunes or small (<0.10 m) proto-dunes at the washover channels to dunes with heights >5 m (Fig. 2a). The average dune height along the island was 2.1 m in May 2004 before Hurricane Ivan caused widespread washover and erosion. Historical (1858-2010; 152 years) and storm-scale (2004-2010; 6 years) shoreline change do not exhibit self-similar behavior across scales (Fig. 3). At swash and surf zone scales (<1000 m), the alongshore variation in historical shoreline change exhibits a log-log linear relationship ($\lambda^{2.3}$), commonly described as brown noise and suggestive of scale invariance, while storm-scale shoreline change exhibits a pink noise spectrum at these scales. The difference between the historical and storm-scale shoreline change is associated with a temporal decoupling in which small-scale and short-term changes during storms are eliminated through the alongshore redistribution of sediment. Both the historical and storm-scale shoreline change at scales >1000 m can be described using a lower order exponent ($\sim\lambda^{1.3}$), which suggests the presence of scale-dependent (or reinforced) structures across the shoreface and along the island.

In contrast to the historical shoreline change, but similar to storm-scale shoreline change, the pre-Ivan dune height exhibits a scale-dependent pink noise spectra (Figs. 2, 3a). The similarity of storm-scale shoreline change and dune height across all scales is associated with a statistically significant coherence, in which areas of greatest shoreline retreat are in areas where the dunes are smaller and discontinuous and less shoreline retreat where the dunes are larger and relatively continuous alongshore (see Houser et al., 2008). As presented in Fig. 5d, the alongshore variation in post-storm dune height recovery (see Houser et al., 2015) exhibits a similar variation to the storm-scale shoreline change and dune height in the GW and CWT (Fig. 4a), although it exhibits a diffusive behavior (~$\lambda^{2.5}$) at the smallest spatial scales (<500 m). It is important to note that recovery data is only available from GI and that this analysis could not be completed on the other islands used in this study.

North Padre Island, Texas

Dunes on PN range in height up to 4.1 m, with an average height of 1.9 m (Fig. 2b). Unlike Gulf Islands, historical shoreline change at PN (1930-200; 77 years) is described by a log-log linear relationship ($\lambda^{2.2}$) across all scales (Fig. 6), consistent with the CWT in Fig. 4b. Storm-scale shoreline change (2001-2007; 6 years) and dune height exhibit similar behavior across all scales, and similar to the results from GI, exhibits a statistically significant coherence in which areas of greatest shoreline retreat are in areas where the dunes are smaller. At swash- and surf-zone scales (<1000 m), the alongshore variation storm-scale shoreline change and dune height can be characterized as pink-noise ($\lambda^{1.2}$), while at larger scales (>1000 m) both exhibit a diffusive behavior consistent with historical shoreline change. At swash- and surf-zone scales the areas of greatest shoreline retreat are associated with areas of smaller dune heights and a greater frequency of washover penetration.

South Padre Island, Texas

The dunes on PS range in height up to 7.8 m, with an average height of 3 m (Fig. 2c). South Padre Island exhibits a behavior similar to that of Gulf Islands in Florida, which also has a ridge and swale bathymetry (see Houser and Mathew, 2011). As shown in Fig. 7, historical shoreline change (1930-2007; 77 years) exhibits a diffusive behavior at the swash- and surf-zone scales ($\lambda^{2.1}$), but can be described by a lower order exponent at scales >1000 m ($\lambda^{1.2}$). Dune height and storm-scale shoreline change (2001-2007; 6 years) can also be characterized by pink noise across all scales, consistent with the variation observed in the CWT (Fig. 4c). The different behavior of storm-scale and historical shoreline change at swash- and surf-zone scales is consistent for both GI and PN. Similar to GI, there is a statistically significant coherence between dune height and storm-scale shoreline change, in which areas of greatest shoreline retreat are associated with areas of smaller dune heights and a greater frequency of washover penetration across all scales.

Matagorda Peninsula, Texas

Dunes on MP reach up to 5.8 m, with an average height of 1.9 m (Fig. 2d). MP exhibits a similar behavior to PN in both the GW (Fig. 8) and the CWT (Fig. 4d). Historical shoreline change (1930-2007; 77 years) exhibits a diffusive behavior across all scales, while dune height and storm-scale shoreline change (2001-2007; 6 years) exhibit a diffusive behavior at scales >1000 m ($\lambda^{2.1}$), and pink noise ($\lambda^{1.1}$) at swash- and surf-zone scales (Fig. 8). Areas of greatest shoreline retreat are associated with areas of smaller dune heights and a greater frequency of washover penetration at swash- and surf-zone scales.

Follets Island, Texas

On Follets Island, the dunes range in height up to 1.15 m, with an average height of 0.59 m (Fig. 2e). Consistent with other islands that do not have a dominant framework geology (e.g. MP and PN), historical shoreline change (1930-2007; 77 years) on FO exhibits diffusive behavior across all scales ($\lambda^{2.1}$; Figure 9). Storm-scale shoreline change (2001-2007; 6 years) exhibits pink noise ($\lambda^{0.85}$) at swash- and surf-zone scales and is diffusive at scales >1000 m. While dune height is also diffusive at scales >1000 m, it is characterized as white noise at surf- and swash-zone scales ($\lambda^{0.12}$). This is the only island in this study in which storm-scale shoreline change and dune heights do not behave similarly or exhibit a statistically significant alongshore coherence, suggesting that the relatively small dunes, and considerable variability of those dunes, does not influence the rate of shoreline retreat at swash- and surf-zone scales. Shoreline erosion is most pronounced at the northern end of the island (-3.9 m yr^{-1}), and decreases to the southern end of the island (-1.5 m yr^{-1}).

Historical Shoreline Retreat and Dune Height Variability

A comparison of historical shoreline retreat and the percent variance at swash- and surf-zone scales is provided in Fig. 10. As noted, the data from the Gulf of Mexico is supplemented by data from Assateague Island, Maryland presented in Hammond (2015). The historical rate of shoreline retreat >10 km south of the Ocean City Inlet is ~0.5 m/year (Hapke et al., 2010), and the swash- and surf-zone scale variability accounts for ~4.8% of the total variance in the dune height (Houser et al., 2013; Hammond, 2015). Greater shoreline retreat is observed for those islands with the greatest % variance at swash- and surf-zone scales compared to the total variance (r^2=0.92, p<0.00). It is important to note that the data for Assateague Island (Hammond, 2015) is for the southern part of the island within the Assateague Island National Seashore, where the Ocean City Inlet does not directly affect island retreat rates and dune morphology (Houser et al., 2012).

Discussion

This study represents the culmination of numerous studies completed by the authors to describe the response and recovery of barrier islands to extreme storms. To explore the patterns observed in those earlier studies, the purpose of the present study is to quantify the alongshore scaling of dune height and where possible dune height in relation to storm-scale (<10 year) and historical (~100 year) shoreline retreat. Specifically, the foredunes on the islands examined in this study are not uniform alongshore and can exhibit considerable variability in height, volume and alongshore extent. Modeling results suggest that the impact of an extreme storm is sensitive to the pre-storm variability of the dune crest elevation (Houser, 2013). While recent evidence suggests that historical shoreline retreat (>75 years) follows a power law, and that a single process (i.e. alongshore transport) dominates across all scales (see Tebbens et al., 2002; Lazarus et al., 2011), there have been no studies to characterize the variability of dune height alongshore. Results of the present study suggest that dune morphology is scale-dependent and reinforced, which suggests that the processes operating at swash- and surf-zone scales (<1000 m) are different than the processes operating at larger scales. The variations in the dune height are reinforced by washover (Houser, 2013; Weymer et al., 2015; Goldstein and Moore, 2017), which occurs on shorter timescales than the recovery of the dune through the expansion of dune-building vegetation (Houser et al., 2015; Goldstein et al., 2016). However, dune heights examined in this study were found to be scale-dependent at the largest scales on islands that have a framework geology that varies alongshore (GI and PS). As shown by Stone et al. (1992), the framework geology at GI leads to a cellular, non-integrated, longshore drift system that does not permit shoreline dissipation as observed on the other islands in this study. The framework geology at GI and PS also results in an alongshore variation in the nearshore and beach state that influences both the aeolian transport potential and availability of sediment within the local littoral cell (see Houser et al., 2008; Houser and Mathew, 2011). Where there is no variation in the framework geology alongshore (e.g. PN, MP, FI), longshore transport and shoreline dissipation are continuous alongshore, leading to similar aeolian transport potential and sediment supply alongshore.

Storm-scale shoreline change (<10 years) and dune height are similar to historical shoreline change at alongshore length scales of >1000 m where the framework geology varies alongshore (e.g. PN and MP). The diffusive behavior suggested by the observed power law ($\lambda^{\sim 2}$) is consistent with the redistribution of sediment alongshore in response to island curvature or other sources of variation in the incident wave field. Without local variations in bathymetry and/or sediment supply and texture, small-scale variations in the shoreline will ultimately be masked by the large-scale gradients over long timescales. Where the bathymetry varies alongshore (e.g. GI and PS), shoreline change and dune height exhibit a pink noise behavior that suggests scale-dependency, which is reflective of the underlying geology. The shelf of both GI and PS is dominated by a ridge and swale bathymetry that creates an alongshore variation in bathymetry, which in turn creates an alongshore variation in sediment supply and aeolian transport potential from beach to dune, based on the frequency of bar welding to the beachface and beach slope, respectively (see Houser, 2009). At the more reflective GI, greater washover penetration and shoreline retreat is observed landward of the swales because of the steep beachface and limited aeolian transport for dune development. In contrast, washover penetration and shoreline retreat are at a maximum landward of the offshore ridges at the more dissipative PS because sediment supply to the dune is limited. This dissimilarity reflects differences in the availability of supply and the aeolian transport potential between dissipative and reflective beaches (Hesp, 2002; Houser, 2009). The scale-dependent nature of shoreline change and dune morphology is consistent with the distinct (littoral) cells in the longshore drift system on Santa Rosa Island described by Stone et al. (1992).

At swash- and surf-zone scales, storm-scale shoreline change and dune height are not diffusive and exhibit a different power-law relationship than historical shoreline retreat. Storm-scale shoreline change and dune height exhibit a scale-dependent behavior ($\lambda^{\sim 1}$) on all islands examined. This suggests that variations in shoreline change and dune height are not dissipated (i.e. equalized) alongshore and that variations can persist, at least for dune height. The variation in storm-scale shoreline change and dune height is found to be coherent at these scales, with greater shoreline retreat associated with smaller dune heights, and limited shoreline retreat or even accretion tend to be found in areas with larger dunes. Combined with the diffusive nature of historical shoreline retreat, this suggests that these small-scale variations (in both space and time) are ultimately eliminated through the alongshore redistribution of sediment resulting from large-scale transport gradients. However, variations in dune height are persistent (Weymer et al., 2015) and small-scale variations can be reinforced through lateral erosion with each storm capable of reaching the backshore and overtopping smaller dunes (Houser, 2013). This suggests that the alongshore variation in storm-scale shoreline retreat is a response to the alongshore variation in the dune, and the difference between whether sediment is lost to the back-barrier through washover or added to the foreshore through dune scarping and erosion.

The dissipation of storm-scale variations of the shoreline is accomplished through alongshore transport, with sediment being moved from the areas of larger dunes and limited erosion (or even accretion) following storms to areas with greater erosion where the dunes are relatively small. This suggests that an increase in washover in areas with smaller or discontinuous dunes will come at the expense of adjacent areas where the dunes are relatively large and continuous alongshore. This is consistent with the observed relationship between the variability of dune height alongshore and historical shoreline retreat; the greater the variability in the dune, the faster that the island transgresses through washover. While greater variability of the dune results in a lower average elevation of the island, the behavior of a variable dune is quite different from that of a relatively uniform dune despite having similar average heights (Houser, 2013). Overwash preferentially flows through the existing dune gaps leading to a deepening and widening of the overwash channel, which in turn reinforces and enhances small-scale variability of the dune alongshore. While short-term shoreline change exhibits an alongshore correspondence with the variation in dune height at surf- and swash-zone scales, alongshore transport over longer timescales leads to a dissipative profile. Assuming no additional sediment from offshore or alongshore sources, the loss of dune sediment to the back of the island through washover leads to shoreline retreat. In this respect, small-scale variations in dune height and volume are a primary control on the rate of island transgression in response to sea-level rise.

We graphically depict this relationship in Fig. 11, showing how variability affects island response to storms. Results suggests that the shoreline is dissipative and tends towards a "straight" morphology (Recovered Profile), while the alongshore variation in dune height may either dissipative slowly (e.g. NP, MP, FI) or be maintained by a dominant framework geology (SP, GI). During a storm, the persistent alongshore variation in the dune controls the alongshore variation in storm response with washover through the gaps or scarping and erosion where the dune height is larger (Storm Impact). Washover leads to a net loss of sediment from the nearshore, beach and dune environment and localized shoreline retreat, while dune scarping and erosion lead to deposition in the nearshore leading to a post-storm shoreline retreat pattern that corresponds to the alongshore variation in dune height. While a larger storm may result in widespread dune erosion and washover, sediment is initially transported through the dune gaps until such time that the larger dunes are breached through scarping or lateral erosion. As the system recovers, the dunes begin to grow in height and the shoreline transitions back towards a straight morphology (Post-storm Recovery). Given sufficient time the infilling of the dune gaps is promoted through expansion of vegetation cover and aeolian transport from beach to dune, but this is much slower than the recovery of the shoreline and typically does not occur before the next storm (see Houser et al., 2015). Recent evidence suggests that washover and aeolian blowout through these gaps can be enhanced by driving on the beach at PN and AS (Houser et al., 2012; Jewell et al., 2014; 2017), which limits dune recovery and reinforces the alongshore variation in dune height and shoreline change.

Unlike dune height, post-storm dune recovery (r) in the present dataset from GI exhibits a diffusive behavior at the smallest spatial scales. This suggests that post-storm dune recovery is not dependent on pre-storm variations in dune height at the smallest scales, although it remains dependent on the pre-storm dune height at larger scales. Recovery at the smallest scales depends on the survival of vegetation and the spread of dune building species through seed dispersal and the extension of rhizomes. The presence of vegetation promotes the capture of sediment transported by the wind from the beach or washover deposits to remove small-scale variations in topography. At larger scales, recovery is dependent on the local topography because the pre-storm morphology of the dune determines storm impact, which in turn determines the presence or absence of vegetation and is another means by which variations in the dune are reinforced. While it is possible for recovery to be diffusive across all scales given sufficient time (see Fig.

3), recent evidence suggests that recovery to pre-storm height (and alongshore variability) can take more than a decade (Houser et al., 2015).

Only if there was an extended period of quiescence could complete vegetation recovery lead to a relatively uniform dune that could be characterized by a diffusive wavelet spectrum. Given the frequency of storm surge at each of the islands studied and predicted increases in the frequency and magnitude of storm events in the future, it is reasonable to expect that the alongshore variation in the dune will persist or become enhanced. Further study with a more comprehensive dataset in time and across additional barrier islands is required to determine how changes in storm activity and specific sequencing of storms will alter island response to relative sea-level rise (see Dissanayake et al., 2015). As described by Anderson et al. (2016), the rate of sea-level rise in parts of the Gulf of Mexico is approaching the rates estimated for the early Holocene and significantly larger than the long-term rate over the past 4000 years. Combined with a lack of sediment supply (from alongshore and offshore sources) and anthropogenic forcing, the rapid rate of sea-level rise may lead to increased island degradation (Duran and Moore, 2015; Pelletier et al., 2016). Results of the present study suggest that FI may have reached a perpetual low-elevation state and that the other islands have the potential to transition towards a low elevation state as a result of rapid sea-level rise and increased frequency of storm scarping and washover. However, further analysis is required to determine if the relationships identified in this study can be used to describe the alongshore scaling of dune height and shoreline retreat on other barrier islands.

Conclusions

The foredune is rarely uniform and can exhibit considerable variation in height and width at a range of length scales. Results of the present study suggest that unlike historical shoreline change, dune morphology on barrier islands in Texas, Florida and Maryland is scale-dependent and that the processes operating at swash- and surf-zone scales (<1000 m) are different than the processes operating at larger scales. Storm-scale shoreline change (~10 years) and dune height exhibit similar scale-dependent variations at swash- (0-100 m) and surf-zone scales (<100-1000 m), and the in-phase nature of this relationship suggests that areas of greater storm-scale shoreline retreat are associated with areas of smaller dunes. The decoupling of storm-scale and historical shoreline change suggests an alongshore redistribution of sediment towards a more diffusive state over time and the importance of variations in the dune to historical shoreline retreat and island migration. Further study is required to determine if the observed relationships are universal and need to be included in predictive modeling of island response to sea-level rise.

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References

Bak, P., 1996. Complexity and Criticality. In How nature works. Springer New York, 1-32.

Brown, L.F., Macon, J,W., 1977. Environmental geologic atlas of the Texas coastal zone: Kingsville area. Bureau of Economic Geology, University of Texas at Austin.

Castelle, B., Ruessink, B.G., Bonneton, P., Marieu, V., Bruneau, N. and Price, T.D., 2010. Coupling mechanisms in double sandbar systems. Part 2: impact on alongshore variability of inner-bar rip channels. Earth Surface Processes and Landforms, *35*(7), 771-781.

Castelle, B., Turner, I.L., Ruessink, B.G. and Tomlinson, R.B., 2007. Impact of storms on beach erosion: Broadbeach (Gold Coast, Australia). Journal of coastal research, 50, p.534.

Clarke, D.W., Boyle, J.F., and Plater, A.J., 2017. Particle-size evidence of barrier estuary regime as a new proxy for ENSO climate variability. Earth Surface Processes and Landforms, 42, 1520-1534.

Claudino-Sales, V., Wang, P., Horwitz, M.H., 2010. Effect of Hurricane Ivan on coastal dunes of Santa Rosa Barrier Island, Florida: characterized on the basis of pre-and post-storm LIDAR surveys. Journal of Coastal Research, 470-484.

Dissanayake, P., Brown, J. and Karunarathna, H., 2015. Impacts of storm chronology on the morphological changes of the Formby beach and dune system, UK. *Natural Hazards and Earth System Sciences*, *15*(7), pp.1533-1543.

Durán, O., Moore, L.J., 2013. Vegetation controls on the maximum size of coastal dunes. Proceedings of the National Academy of Sciences, 110(43), 17217-17222.

Elko, N., Brodie, K., Stockdon, H., Nordstrom, K., Houser, C., McKenna, K., Moore, L., Rosati, J., Ruggiero, P., Thuman, R. and Walker, I., 2016. *Dune management challenges on developed coasts*. USACE ERDC Vicksburg United States.

Farge, M., 1992. Wavelet transforms and their applications to turbulence. *Annual review of fluid mechanics*, *24*(1), pp.395-458.

Fisk, H.N., 1959. Padre Island and the Laguna Madre flats, coastal south Texas.

Gibeaut, J.C., White, W.A., Hepner, T., Gutierrez, R., Tremblay, T.A., Smyth, R., Andrews, J., 2000. Texas shoreline change project; Gulf of Mexico shoreline change from the Brazos River to Pass Cavallo. A Report of the Texas Coastal Coordination Council.

Goldstein, E.B. and Moore, L.J., 2016. Stability and bistability in a one-dimensional model of coastal foredune height. *Journal of Geophysical Research: Earth Surface*, *121*(5), 964-977.

Goldstein, E.B., Moore, L.J. and Vinent, O.D., 2017. Lateral vegetation growth rates exert control on coastal foredune hummockiness and coalescing time. *Earth Surface Dynamics*, *5*(3), 417.

Hammond, B., 2015. *Rate of Post-Hurricane Barrier Island Recovery* (Doctoral dissertation).

Hansom, J.D., 2001. Coastal sensitivity to environmental change: a view from the beach. Catena, 42(2), 291-305.

Hapke, C.J., Lentz, E.E., Gayes, P.T., McCoy, C.A., Hehre, R., Schwab, W.C. and Williams, S.J., 2010. A review of sediment budget imbalances along Fire Island, New York: can nearshore geologic framework and patterns of shoreline change explain the deficit?. *Journal of Coastal Research*, pp.510-522.

Hesp, P., 2002. Foredunes and blowouts: initiation, geomorphology and dynamics. Geomorphology, 48(1), 245-268.

Héquette, A., Ruz, M.H., 1991. Spit and barrier island migration in the southeastern Canadian Beaufort Sea. Journal of Coastal Research, 677-698.

Houser, C., 2009. Synchronization of transport and supply in beach-dune interaction. Progress in Physical Geography, 33, 733-746. doi:10.1177/0309133309350120

Houser, C., 2012. Feedback between ridge and swale bathymetry and barrier island storm response and transgression. Geomorphology, 173/174, 1-16.

Houser, C., 2013. Alongshore variation in beach-dune morphology: Implications for barrier island response. Geomorphology, 199, 48-61.

Houser, C., Hamilton, S., 2009. Sensitivity of post-hurricane beach and dune recovery to event frequency. Earth Surface Processes and Landforms, 34, 613-628.

Houser, C., Mathew, S., 2011. Variability in foredune height depends on the alongshore correspondence of transport potential and sediment supply. Geomorphology, 125, 62-72.

Houser, C., Hapke, C., Hamilton, S., 2008. Controls on Coastal Dune Morphology, Shoreline Erosion and Barrier Island Response to Extreme Storms. Geomorphology, 100, 223-240.

Houser, C., Labude, B., Haider, L., Weymer, B., 2012. Impacts of Driving on the Beach: Case Studies from Assateague Island and Padre Island National Seashores. Ocean and Coastal Management, 71, 33-45.

Houser, C., Wernette, P., Rentschler, T., Jones, H., Hammond, B., Trimble, S., 2015. Post-storm beach and dune recovery: implications for barrier island resilience. Geomorphology, 234, 54-63.

Jewell, M., Houser, C., Trimble, S., 2014. Initiation and evolution of blowouts within Padre Island National Seashore. Ocean and Coastal Management, 95, 156-164.

Jewell, M., Houser, C. Trimble, S., 2017. Phases of blowout initiation and stabilization on Padre Island revealed through ground-penetrating radar and remotely sensed imagery. *Physical Geography*, 1-22.

Kratzmann, M.G., Hapke, C.J., 2010. Quantifying anthropogenically driven morphologic changes on a barrier island: Fire Island National Seashore, New York. *Journal of Coastal Research*, *28*(1), 76-88.

Lazarus, E., Ashton, A., Murray, A.B., Tebbens, S., Burroughs, S., 2011. Cumulative versus transient shoreline change: Dependencies on temporal and spatial scale. Journal of Geophysical Research: Earth Surface, 116(F2).

Leatherman, S. P. 1976. Barrier island dynamics: overwash processes and solian transport. Coastal Engineering Proceedings 1(15).

Lentz, E.E. and Hapke, C.J., 2011. Geologic framework influences on the geomorphology of an anthropogenically modified barrier island: assessment of dune/beach changes at Fire Island, New York. *Geomorphology*, *126*(1), 82-96.

Li, Y., Lark, M. and Reeve, D., 2005. Multi-scale variability of beach profiles at Duck: a wavelet analysis. *Coastal Engineering*, *52*(12), 1133-1153.

Masetti, R., Fagherazzi, S., Montanari, A., 2008. Application of a barrier island translation model to the millennial-scale evolution of Sand Key, Florida.Continental Shelf Research, 28(9), 1116-1126.

Mathewson, C.C., Minter, L.L., 1976. Impact of water resource development on coastal erosion, Brazos River, Texas. Texas Water Resources Institute.

McGowen, J.H., Brewton, J.L., 1975. Historical changes and related coastal processes, Gulf and mainland shorelines, Matagorda Bay area, Texas. Bureau of Economic Geology, University of Texas at Austin.

McGowen, J.H., Scott, A.J., 1975. Hurricanes as geologic agents on the Texas coast. Estuarine research, 2, 23-46.

Mackintosh, B. 1982. Assateague Island National Seashore: An Administrative History. Department of the Interior: Washington, D.C. 165p

McNinch, J., 2004. Geologic control in the nearshore: shore-oblique sandbars and shoreline erosional hotspots, Mid-Atlantic Bight, USA. Marine Geology, 211, 121-141.

Mitasova, H., Overton, M.F., Recalde, J.J., Bernstein, D.J. and Freeman, C.W., 2009. Raster-based analysis of coastal terrain dynamics from multitemporal lidar data. *Journal of Coastal Research*, pp.507-514.

Mitasova, H., Hardin, E., Starek, M.J., Harmon, R.S. and Overton, M.F., 2011. Landscape dynamics from LiDAR data time series. *Geomorphometry*, pp.3-6.

Morton, R.A., 1977. Historical Shoreline Changes and Their Causes, Texas Gulf Coast (1).

Morton, R.A., 1979. Temporal and spatial variations in shoreline changes and their implications, examples from the Texas Gulf Coast. Journal of Sedimentary Research, 49(4).

Morton, R.A., 2002. Factors controlling storm impacts on coastal barriers and beaches – a preliminary basis for near real-time forecasting. Journal of Coastal Research 18, 486–501.

Morton, R.A., Pieper, M.J., 1975. Shoreline changes on Matagorda Peninsula and San Jose Island.

Murray, A.B., 2007. Reducing model complexity for explanation and prediction. Geomorphology, 90(3), 178-191.

Pelletier, J.D., Brad Murray, A., Pierce, J.L., Bierman, P.R., Breshears, D.D., Crosby, B.T., Ellis, M., Foufoula-Georgiou, E., Heimsath, A.M., Houser, C. Lancaster, N., 2015. Forecasting the response of Earth's surface to future climatic and land use changes: A review of methods and research needs. *Earth's Future*, *3*(7), 220-251.

Psuty, N.P., 1992. Spatial variation in coastal foredune development. In: Carter, R.W.G., Curtis, T.G.F., Sheehy-Skeffington, M.J. (Eds.), Coastal Dunes: Geomorphology, Ecology and Management for Conservation. Balkema Rotterdam, 3–13.

Ruessink, B.G., Coco, G., Ranasinghe, R. and Turner, I.L., 2006. A cross-wavelet study of alongshore nonuniform nearshore sandbar behavior. In *Neural Networks, 2006. IJCNN'06. International Joint Conference on* (pp. 4310-4317). IEEE.

Sallenger, A.H., 2000. Storm impact scale for barrier islands. Journal of Coastal Research 16, 890–895

Schwab, W.C., Thieler, E.R.F., Allen, J.R., Foster, D.S., Swift, B.A., Denny, J.F., 2000. Influence of inner-continental shelf geologic framework on the evolution and behaviour of the barrier-island system between Fire Island Inlet and Shinnecock, Journal of Coastal Research, 408-422.

Schwab, W.C., Baldwin, W.E., Denny, J.F., Hapke, C.J., Gayes, P.T., List, J.H. and Warner, J.C., 2014. Modification of the Quaternary stratigraphic framework of the inner-continental shelf by Holocene marine transgression: an example offshore of Fire Island, New York. *Marine Geology*, *355*, pp.346-360.

Schwartz, R. 20 Nov. 2014. "Hurricanes and Maryland." Hurricanes and the Middle Atlantic States. Blue Diamond Books, Web.

Shalowitz, A.L., 1964. Shore and Sea Boundaries. Publication 10-1, U.S. Department of Commerce, Washington, DC. 749 pp.

Sherman, D.J., Hales, B.U., Potts, M.K., Ellis, J.T., Liu, H., Houser, C., 2013. Impacts of Hurricane Ike on the beaches of the Bolivar Peninsula, TX, USA. *Geomorphology*, *199*, 62-81.

Smith, C.G., Culver, S.J., Riggs, S.R., Ames, D., Corbett, D.R. Mallinson, D., 2008. Geospatial analysis of barrier island width of two segments of the Outer Banks, North Carolina, USA: anthropogenic curtailment of natural self-sustaining processes. *Journal of Coastal Research*, 70-83.

Stallins, J.A., Parker, A.J., 2003. The influence of complex systems interactions on barrier island dune vegetation pattern and process. Annals of the Association of American Geographers 93, 13–29

Stockdon, H.F., Sallenger, A.H., Holman, R.A., Howd, P.A., 2007. A simple model for the spatially-variable coastal response to hurricanes. Marine Geology, 238, 1–20.

Stockdon, H.F., Doran, K.S. and Sallenger Jr, A.H., 2009. Extraction of lidar-based dune-crest elevations for use in examining the vulnerability of beaches to inundation during hurricanes. *Journal of Coastal Research*, pp.59-65.

Stone, G.W., Stapor, F.W., May, J.P. Morgan, J.P., 1992. Multiple sediment sources and a cellular, non-integrated, longshore drift system: Northwest Florida and southeast Alabama coast, USA. *Marine Geology*, *105*(1-4), 141-154.

Tebbens, S.F., Burroughs, S.M., Nelson, E.E., 2002. Wavelet analysis of shoreline change on the Outer Banks of North Carolina: An example of complexity in the marine sciences. Proceedings of the National Academy of Sciences, 99(suppl 1), 2554-2560.

Thieler, E.R., Young, R.S., 1991. Quantitative evaluation of coastal geomorphological changes in South Carolina after Hurricane Hugo. Journal of Coastal Research, 8, 187–200.

Thornberry-Ehrlich, T.L., 2005. Assateague Island National Seashore geologic resource management issues scoping summary. *Submitted to the National Park Service*.

Torrence, C. and Compo, G.P., 1998. A practical guide to wavelet analysis. *Bulletin of the American Meteorological society*, *79*(1), pp.61-78.

Walker, I.J., Davidson-Arnott, R.G., Bauer, B.O., Hesp, P.A., Delgado-Fernandez, I., Ollerhead,

J. Smyth, T.A., 2017. Scale-dependent perspectives on the geomorphology and evolution of beach-dune systems. *Earth-Science Reviews*.

Weise, B.R., White, W.A., 1980. Padre Island National Seashore: A guide to the geology, natural environments, and history of a Texas barrier island(Vol. 17). Bureau of Economic Geology, University of Texas at Austin.

Wernette, P., Houser, C., Bishop, M., 2016. Technical Communication: An automatic approach for extracting barrier island morphology from digital elevation models. Geomorphology, 262, 1-7.

Weymer, B.A., Houser, C., Giardino, J.R., 2015. Poststorm evolution of beach-dune morphology: Padre Island National Seashore, Texas. Journal of Coastal Research, 31(3), 634-644.

Wilkinson, B.H., Basse, R.A., 1978. Late Holocene history of the central Texas coast from Galveston Island to Pass Cavallo. Geological Society of America Bulletin, 89(10), pp.1592-1600.

Wilkinson, B.H., McGowen, J.H., 1977. Geologic approaches to the determination of historical coastal recession rates, Matagorda peninsula, Texas. Environmental Geology, 1, 359-365.

Wolner, C.W., Moore, L.J., Young, D.R., Brantley, S.T., Bissett, S.N. and McBride, R.A., 2013. Ecomorphodynamic feedbacks and barrier island response to disturbance: Insights from the Virginia Barrier Islands, Mid-Atlantic Bight, USA. *Geomorphology*, *199*, pp.115-128.

Table 1. Source of LiDAR and shoreline change data used to quantify the alongshore variation in dune height, and both long-term and short-term shoreline change.

	LiDAR Data	Shoreline Change
Gulf Islands	**May 2004**: Compact Hydrographic Airborne Rapid Total Survey (CHARTS) **September 2004 and 2005:** EAARL (Experimental Advanced Airborne Research LIDAR) **2006:** Escambia County **2010:** USACE Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX) using the Hawkeye system	**1858 to 2010 long-term and storm-scale shoreline change:** NOAA T-sheets, digitally rectified aerial photographs, USGS Digital Orthophoto Quad (DOQ), ground GPS survey, LiDAR **Source:** Houser *et al.* (2008)
South Padre Island	**2009**: USACE Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX) using the Optech ALTM Gemini System (NOAA Digital Coast)	**1930 to 2007 long-term and storm-scale shoreline change:** NOAA T-sheets, digitally rectified aerial photographs, USGS Digital Orthophoto Quad (DOQ), ground GPS survey, LiDAR **Source:** University of Texas at Austin Bureau of Economic Geology
North Padre Island	**2005:** USGS and National Park Service using NASA's Experimental Advanced Airborne Research LiDAR (NOAA Digital Coast)	
Matagorda Island	**2009**: USACE Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX) using the Optech ALTM Gemini System (NOAA Digital Coast)	
Follets Island	**2001**: USGS using NASA's Airborne Topographic Mapper (ATM) laser scanner (NOAA Digital Coast)	
Assateague Island	**2005:** USGS and National Park Service using NASA's Experimental Advanced Airborne Research LiDAR (NOAA Digital Coast)	

Figure Headings

Figure 1. Location of study sites Gulf Islands (GI), North Padre Island (PN), South Padre Island (PS), Matagorda Peninsula (MP), Folletts Island (FO) and Assateague Island (AI)

Figure 2. Alongshore variation in dune height for Gulf Islands (GI), North Padre Island (PN), South Padre Island (PS), Matagorda Peninsula (MP), and Folletts Island (FO) .

Figure 3. Log-log wavelet plots of dune height (Pre-Hurricane Ivan, May 2004), historical shoreline change (100 years), storm-scale shoreline change (10 years), and dune recovery rate for Gulf Islands in northwest Florida. Best fit power functions are presented adjacent to the results of the non-linear regression analysis.

Figure 4. Continuous wavelet transformations (CWT) for dune height at (a) Gulf Islands National Seashore (pre-Ivan), (b) Gulf Islands National Seashore (post-Ivan) (c) North Padre Island, (d) South Padre Island, (e) Matagorda Peninsula, and (f) Follets Island. Red areas are associated with greater variance at a given alongshore scale. Note that different scales are used for each island to highlight the structure of the variance alongshore.

Figure 5. Continuous wavelet transformations (CWT) for dune height 1, 2 and 5 years following Hurricane Ivan, and the CWT for the rate (r) of dune recovery (see Houser et al., 2015) at Gulf Islands National Seashore. Note that different scales are used in this image to highlight the structure of the variance alongshore.

Figure 6. Log-log wavelet plots of dune height, historical shoreline change (100 years), and storm-scale shoreline change (10 years) for North Padre Island, Texas. Best fit power functions are presented adjacent to the results of the non-linear regression analysis.

Figure 7. Log-log wavelet plots of dune height, historical shoreline change (100 years), and storm-scale shoreline change (10 years) for South Padre Island, Texas. Best fit power functions are presented adjacent to the results of the non-linear regression analysis.

Figure 8. Log-log wavelet plots of dune height, historical shoreline change (100 years), and storm-scale shoreline change (10 years) for Matagorda Peninsula, Texas. Best fit power functions are presented adjacent to the results of the non-linear regression analysis.

Figure 9. Log-log wavelet plots of dune height, historical shoreline change (50 years), and storm-scale shoreline change (10 years) for Follets Island, Texas. Best fit power functions are presented adjacent to the results of the non-linear regression analysis.

Figure 10. Correlation between Historical Shoreline Retreat (m yr^{-1}) and the % variability associated with surf and swash-zone scale variations in the dune.

Figure 11. Conceptual model of how variability of the dune at swash and surf zone scales persists during and following storms. Short-term shoreline change exhibits an alongshore correspondence with the variation in the dune line at these scales, and the alongshore dissipation

of this variation over longer timescales influences the rate of shoreline retreat..

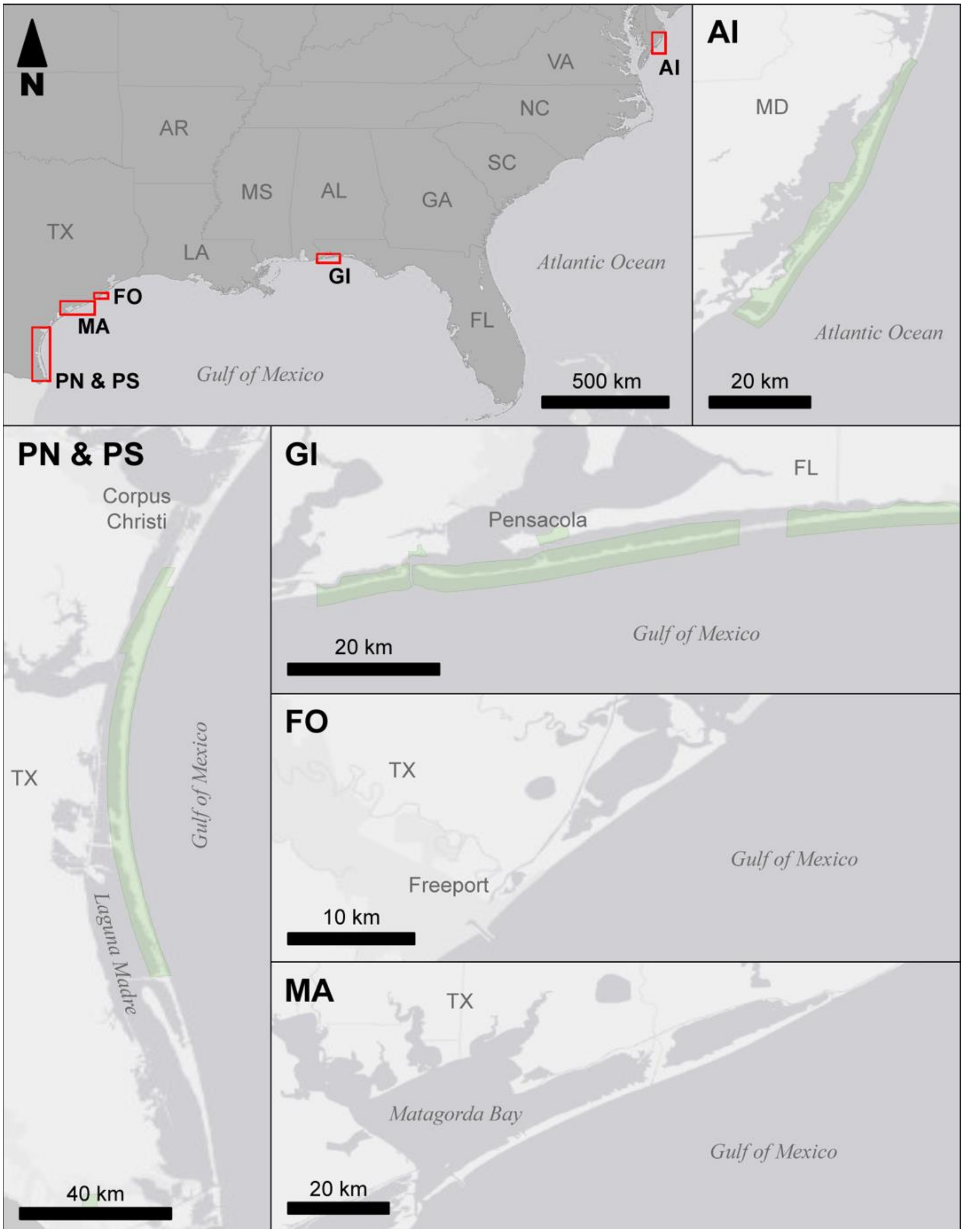

N
VA
AI
NC
AR
SC
MS
AL
GA
TX
LA
GI
Atlantic Ocean
FO
MA
FL
PN & PS
Gulf of Mexico
500 km
AI
MD
Atlantic Ocean
20 km
PN & PS
Corpus Christi
TX
Gulf of Mexico
Laguna Madre
40 km
GI
FL
Pensacola
Gulf of Mexico
20 km
FO
TX
Gulf of Mexico
Freeport
10 km
MA
TX
Matagorda Bay
Gulf of Mexico
20 km

Figure 1

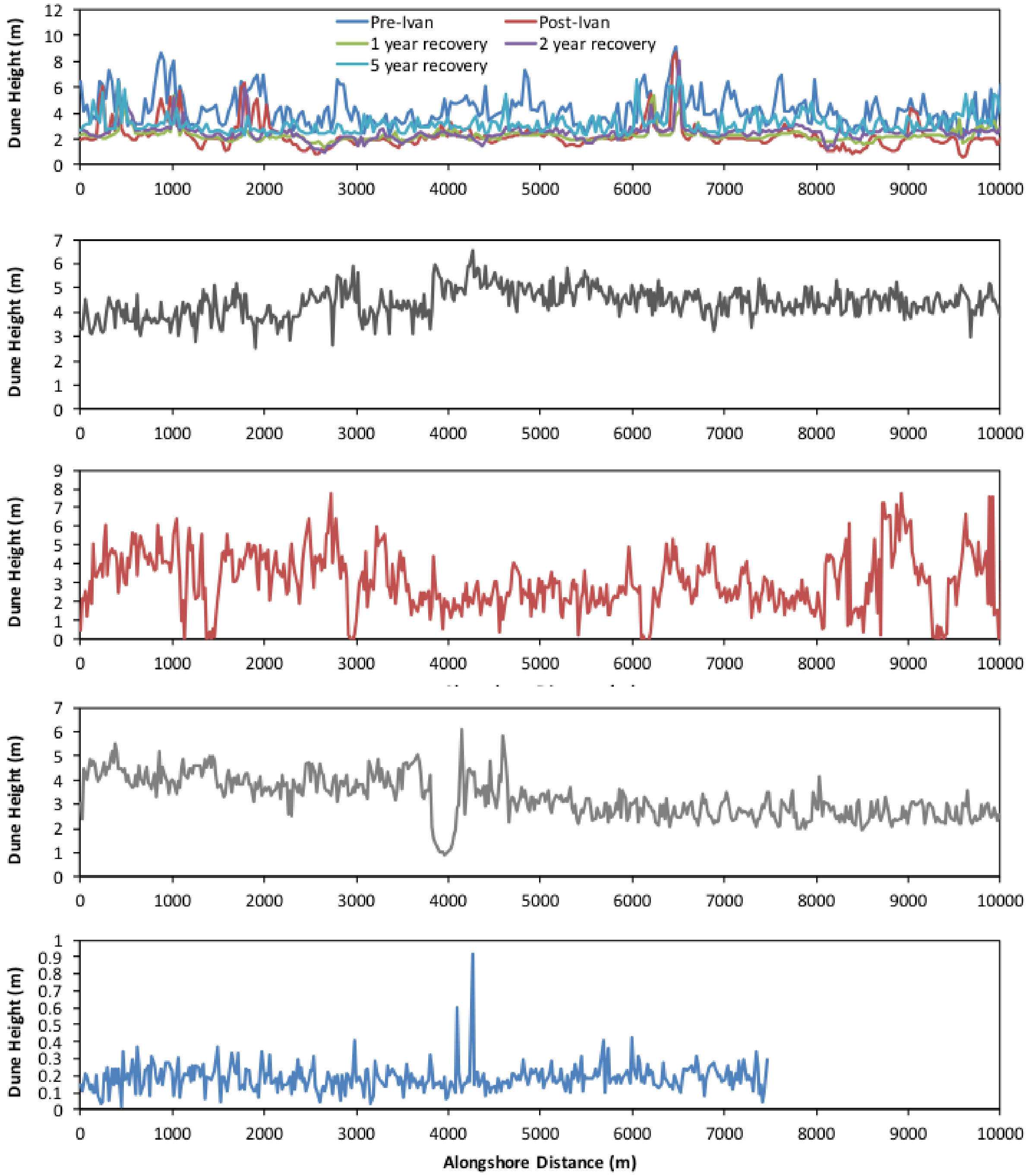

Pre-Ivan
Post-Ivan
1 year recovery
2 year recovery
5 year recovery
Dune Height (m)
Alongshore Distance (m)

Figure 2

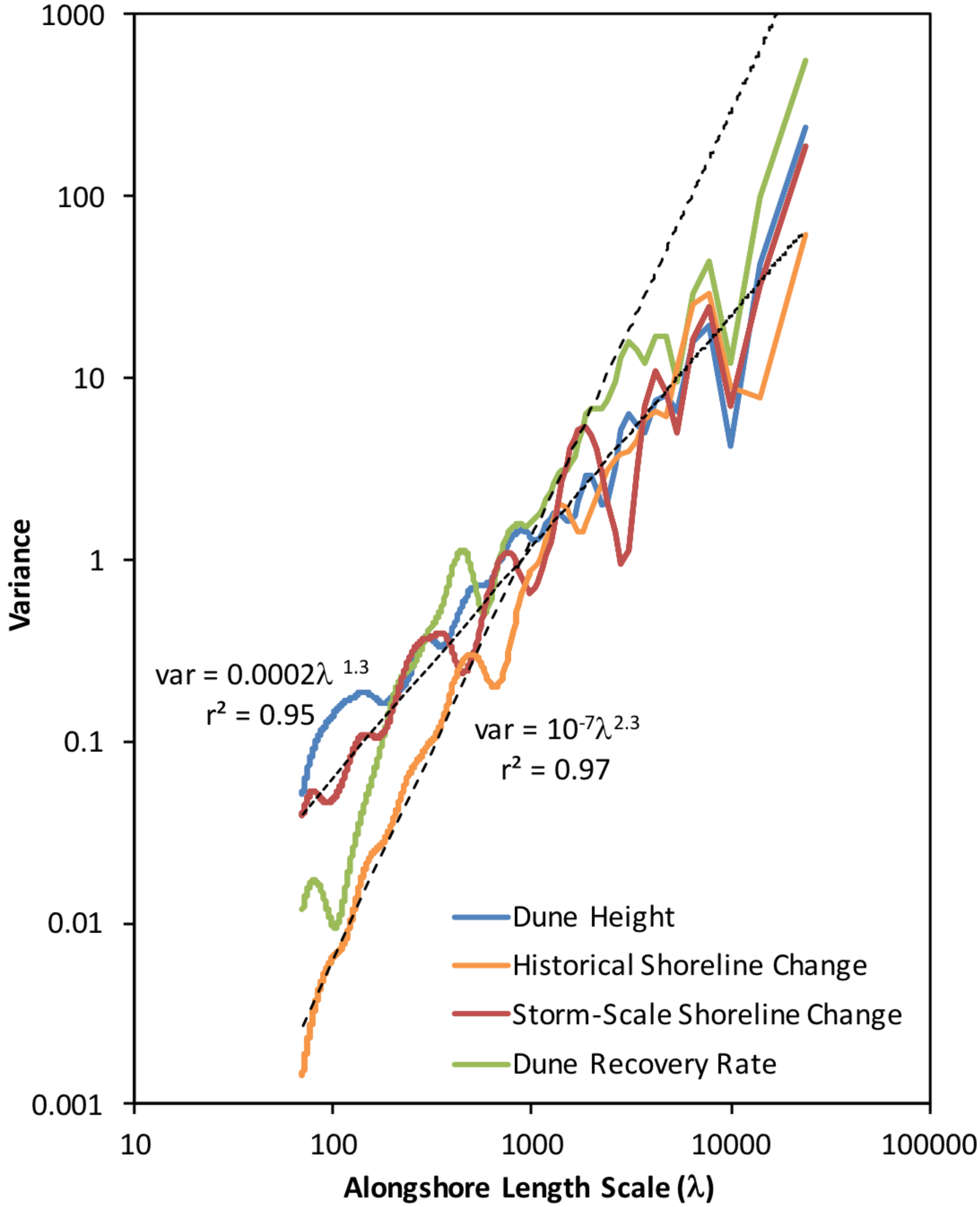

1000
100
10
1
0.1
0.01
0.001
Variance
var = 0.0002λ 1.3
r² = 0.95
var = 10-7λ2.3
r² = 0.97
Dune Height
Historical Shoreline Change
Storm-Scale Shoreline Change
Dune Recovery Rate
10
100
1000
10000
100000
Alongshore Length Scale (λ)

Figure 3

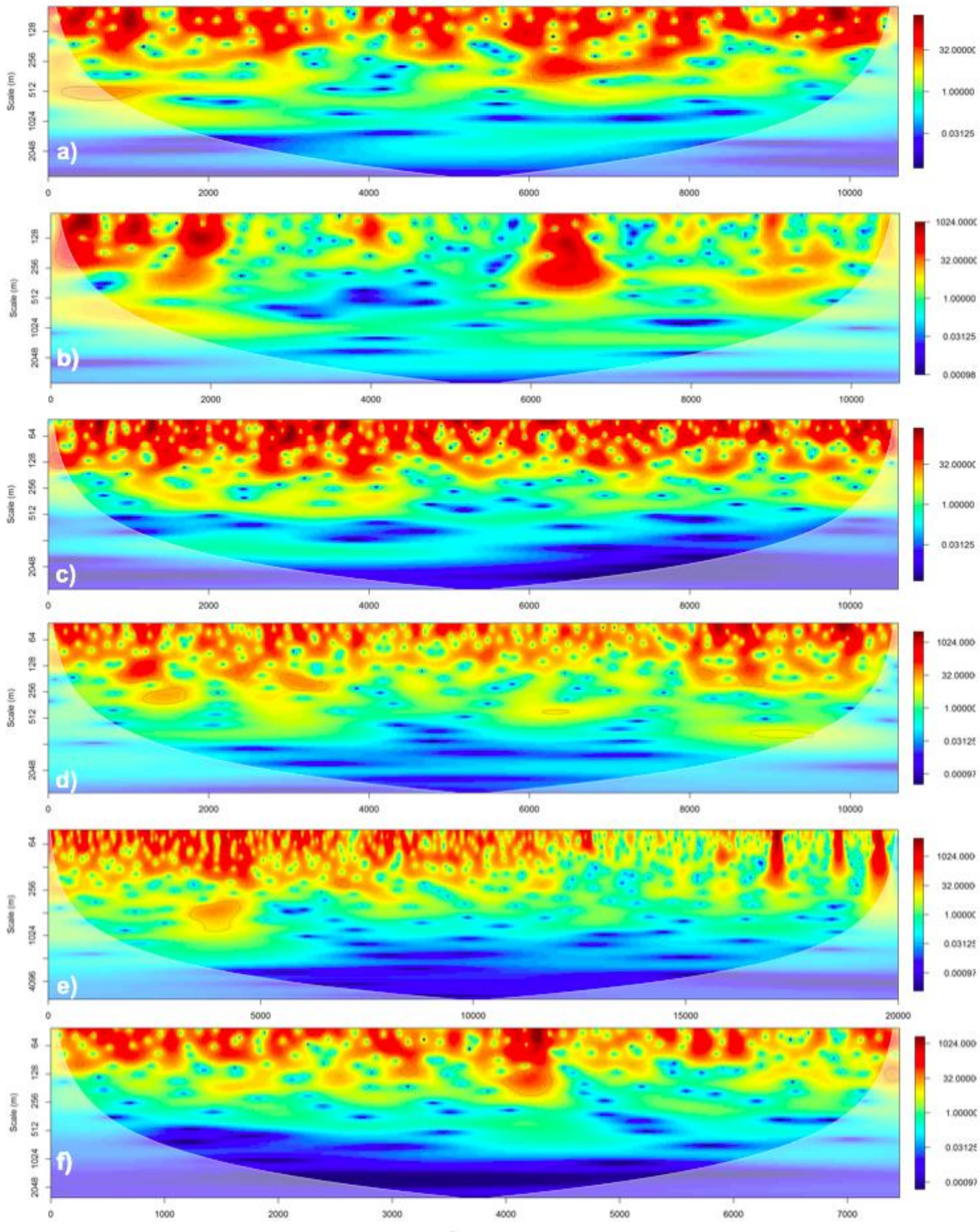
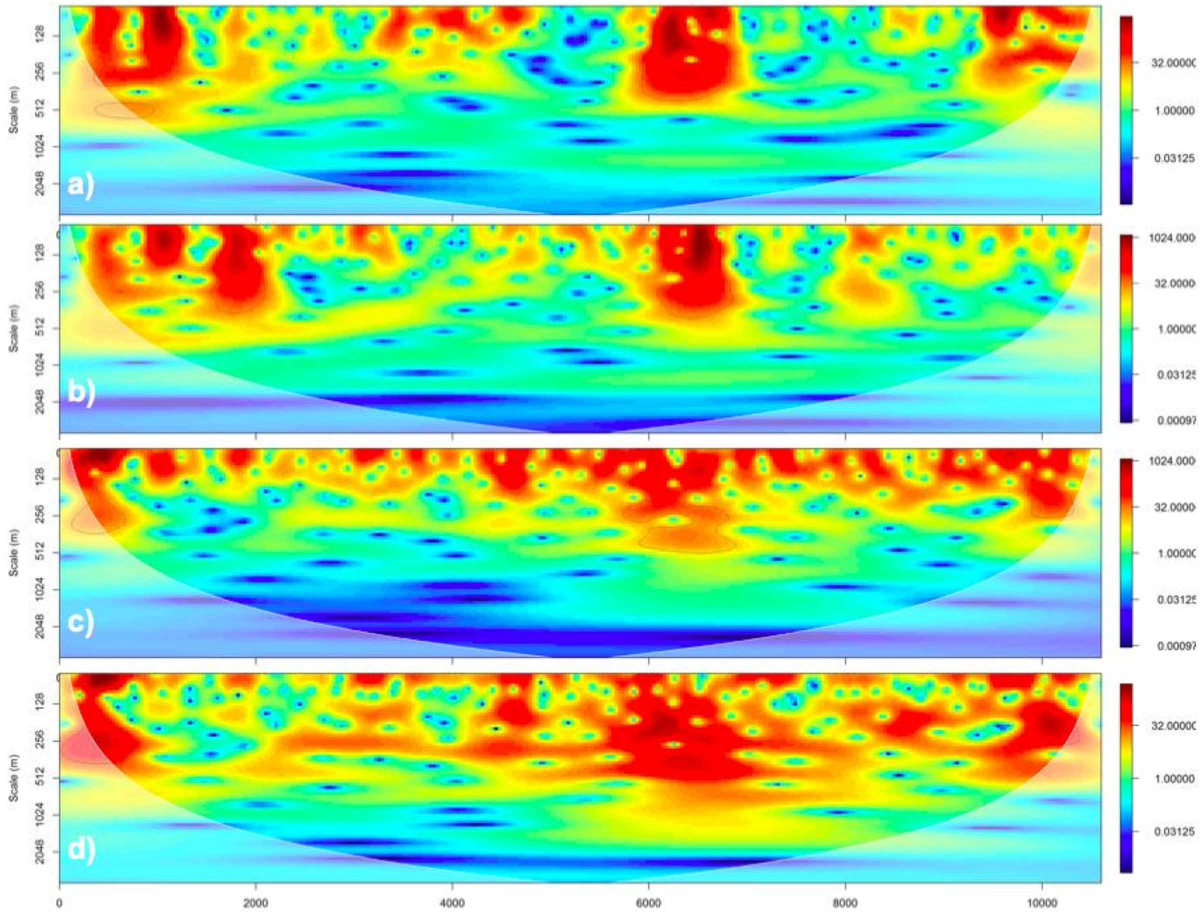
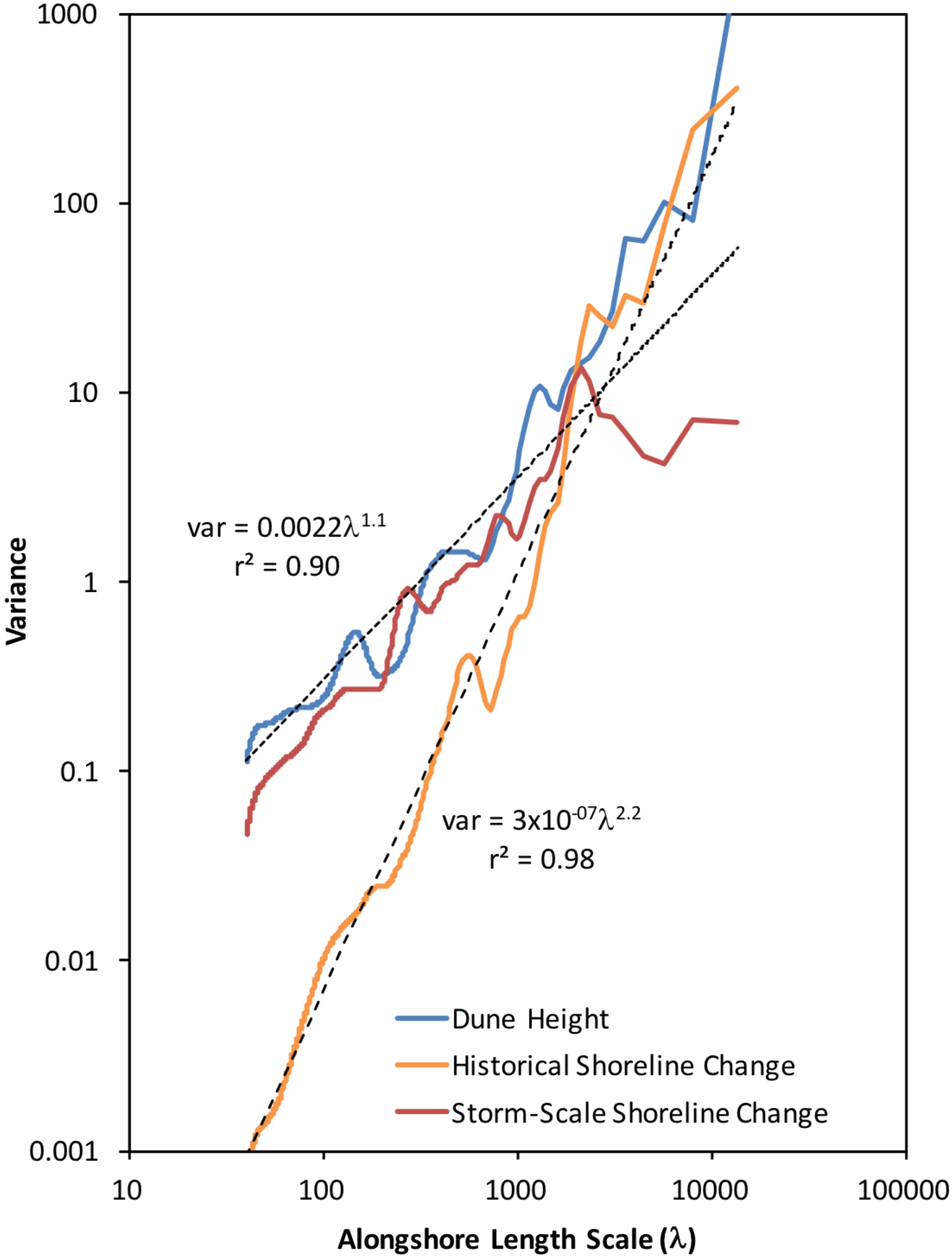


Figure 4



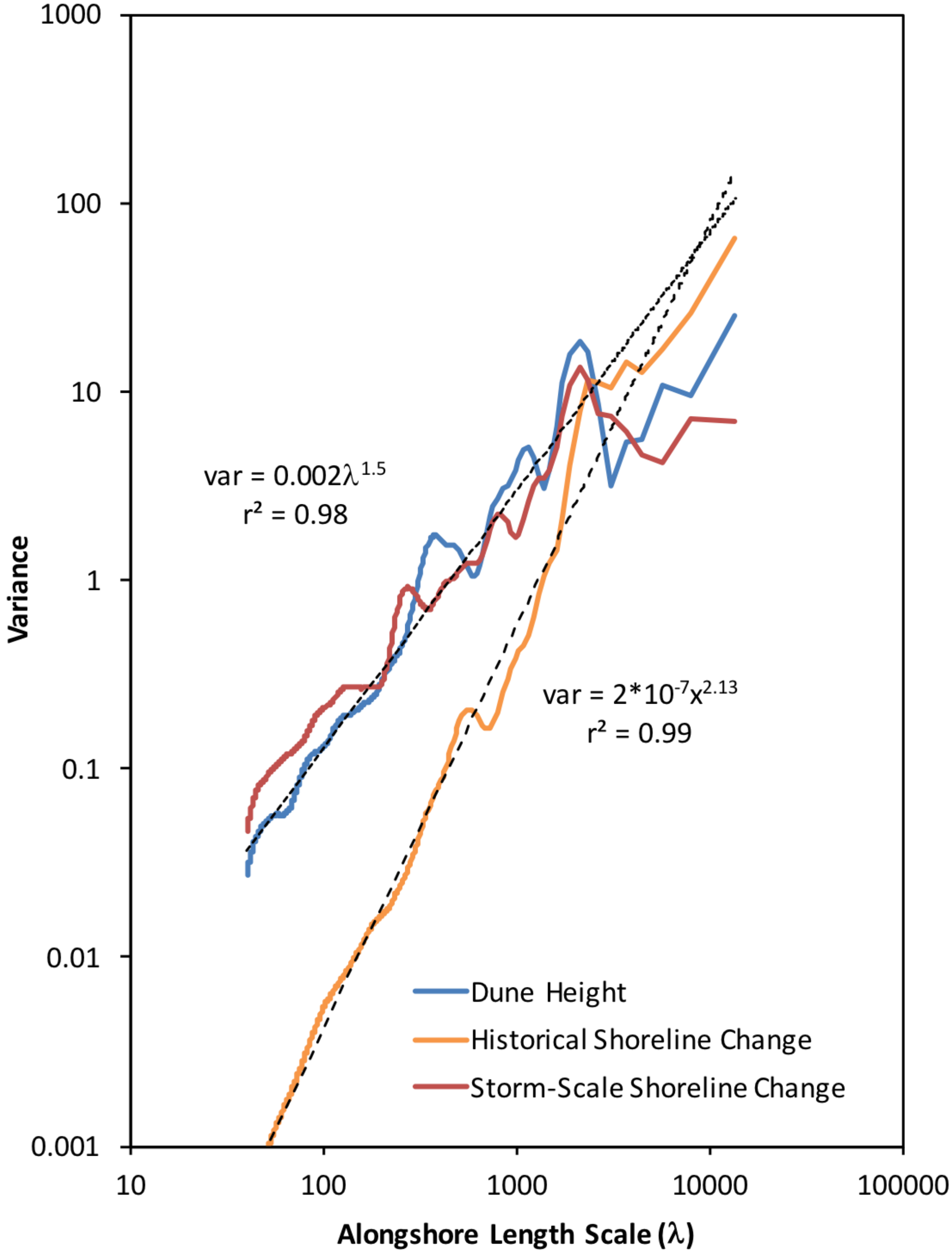
Scale (m)
128
256
512
1024
2048
a)
b)
c)
d)
32.00000
1.00000
0.03125
1024.000
0.00097
0
2000
4000
6000
8000
10000

Figure 5



1000
100
10
1
0.1
0.01
0.001
10
100
1000
10000
100000
Variance
Alongshore Length Scale (λ)
var = 0.0022λ^1.1
r² = 0.90
var = 3x10^-07λ^2.2
r² = 0.98
Dune Height
Historical Shoreline Change
Storm-Scale Shoreline Change

Figure 6



1000
100
10
1
0.1
0.01
0.001
Variance
var = 0.002λ^1.5
r² = 0.98
var = 2*10^-7x^2.13
r² = 0.99
Dune Height
Historical Shoreline Change
Storm-Scale Shoreline Change
10
100
1000
10000
100000
Alongshore Length Scale (λ)

Figure 7

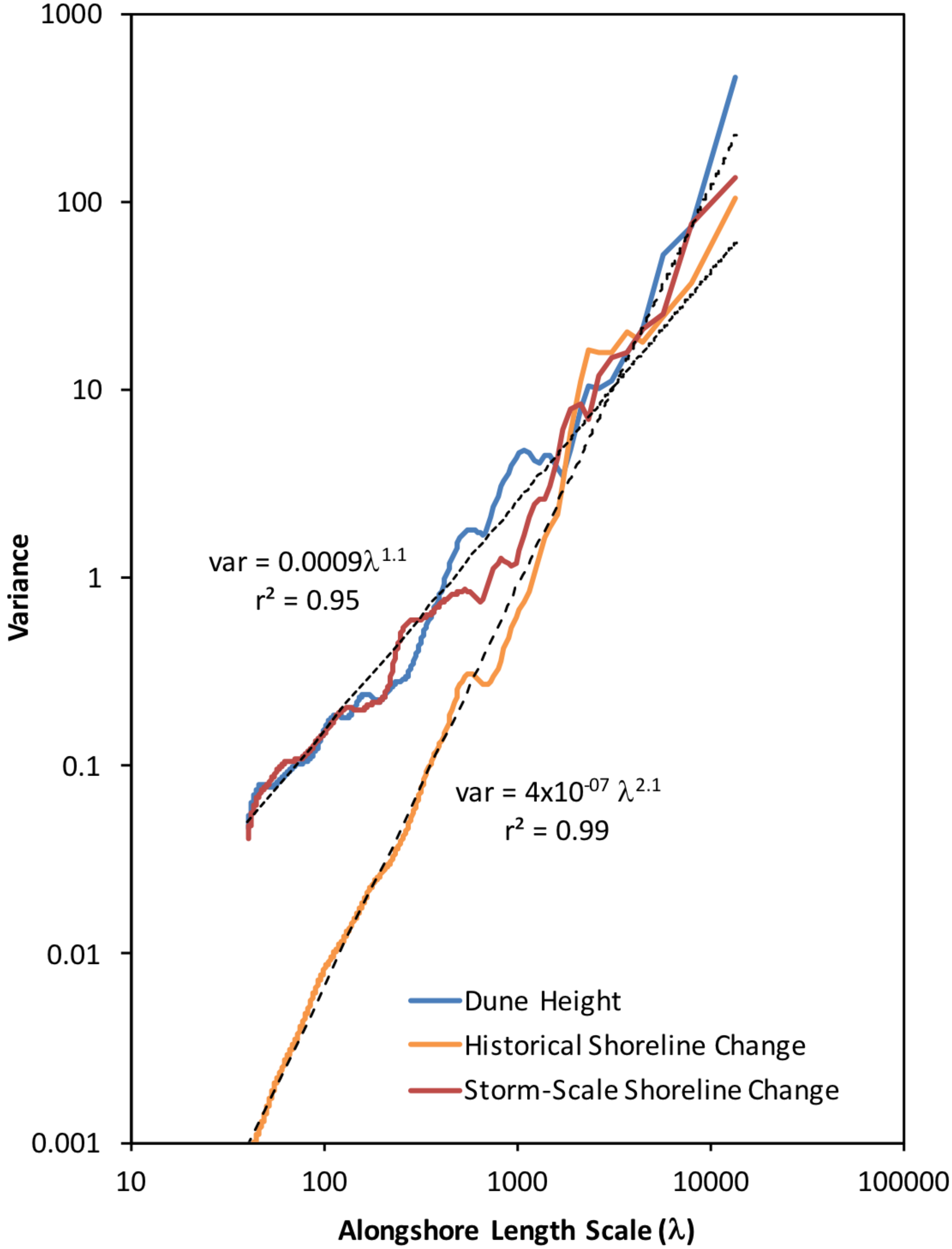
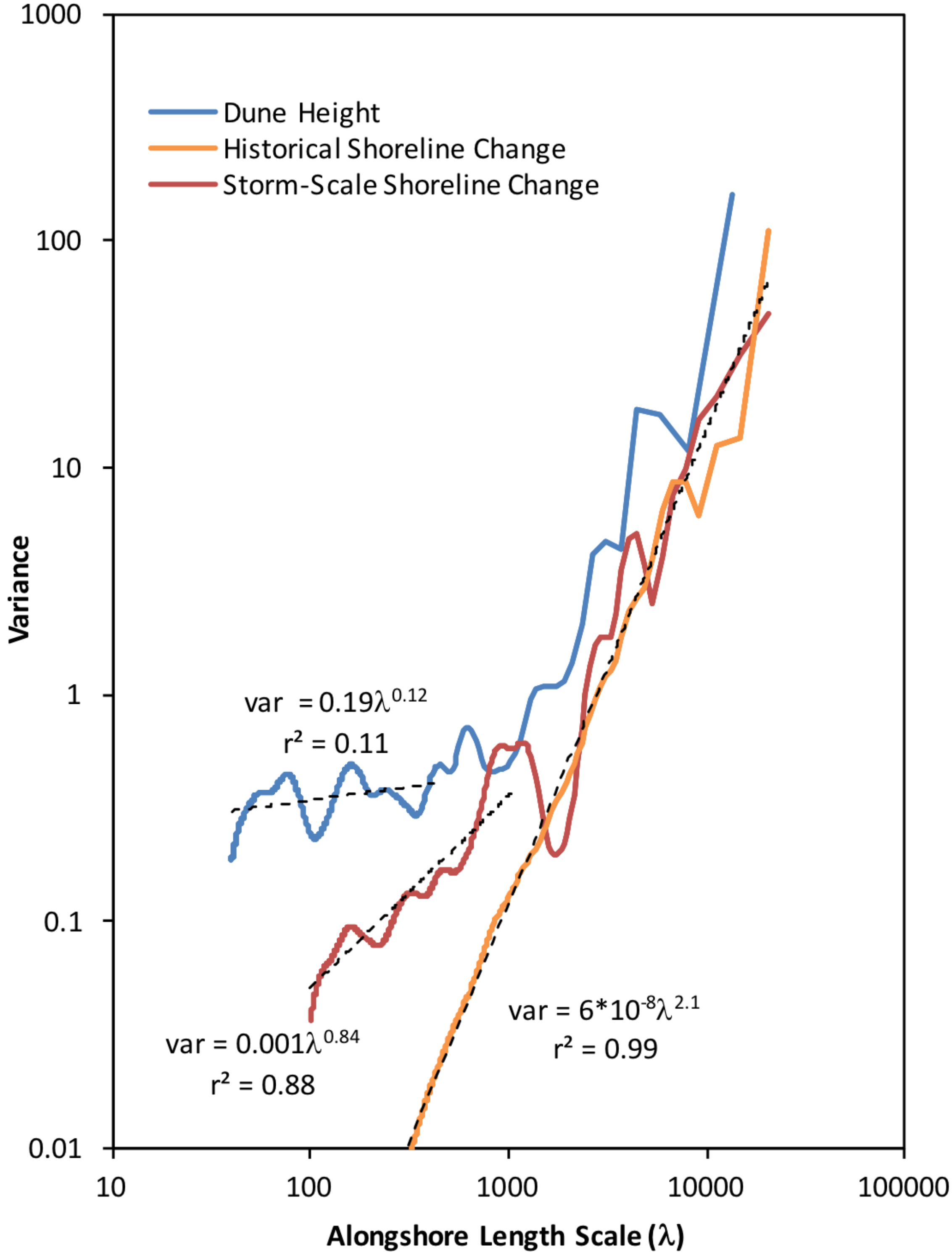
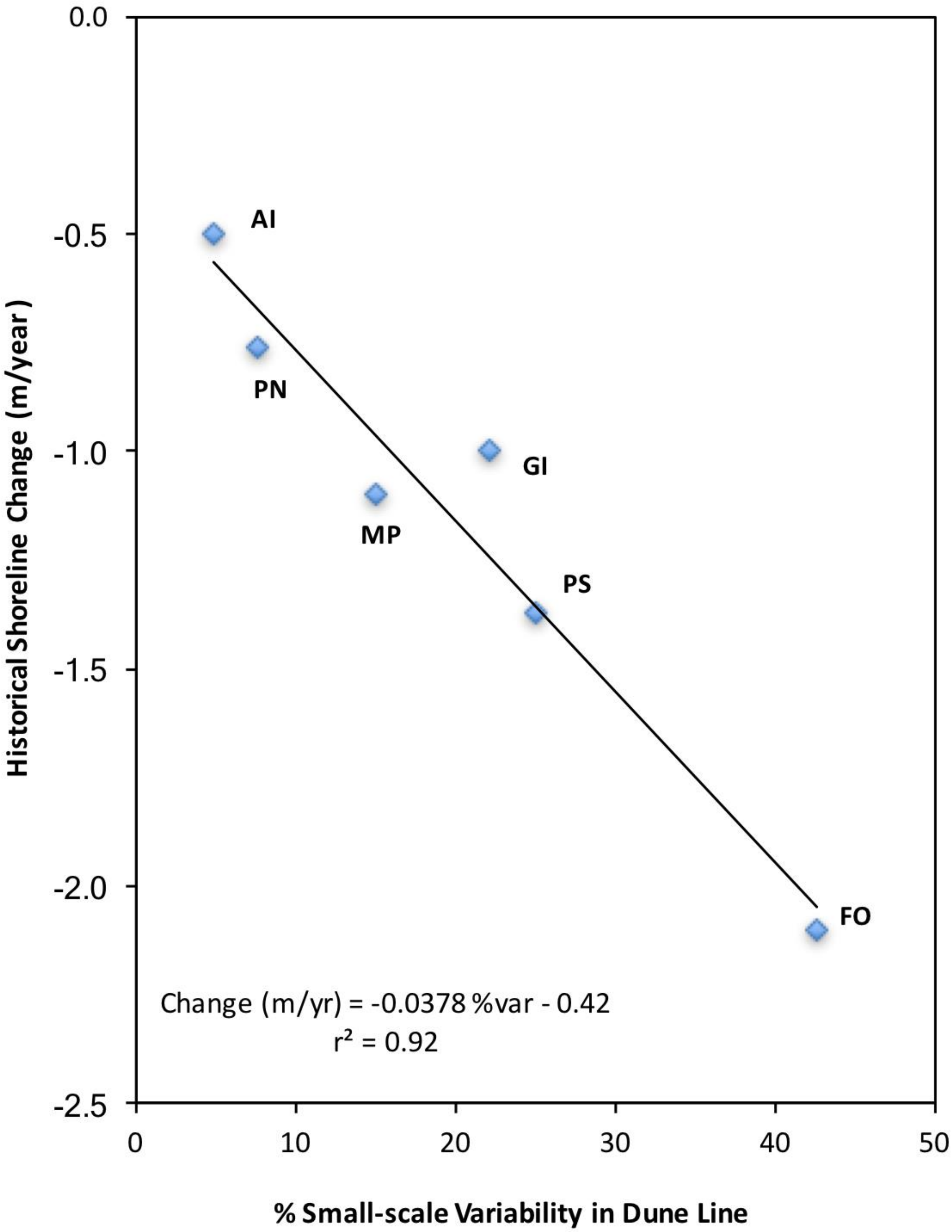

1000
100
10
1
0.1
0.01
0.001
Variance
10
100
1000
10000
100000
Alongshore Length Scale (λ)
var = 0.0009λ^1.1
r² = 0.95
var = 4x10^-07 λ^2.1
r² = 0.99
Dune Height
Historical Shoreline Change
Storm-Scale Shoreline Change

Figure 8



1000
100
10
1
0.1
0.01
Variance
Dune Height
Historical Shoreline Change
Storm-Scale Shoreline Change
var = 0.19λ^0.12
r² = 0.11
var = 0.001λ^0.84
r² = 0.88
var = 6*10^-8λ^2.1
r² = 0.99
10
100
1000
10000
100000
Alongshore Length Scale (λ)

Figure 9



0.0
-0.5
-1.0
-1.5
-2.0
-2.5
AI
PN
GI
MP
PS
FO
Historical Shoreline Change (m/year)
Change (m/yr) = -0.0378 %var - 0.42
r² = 0.92
0
10
20
30
40
50
% Small-scale Variability in Dune Line

Figure 10

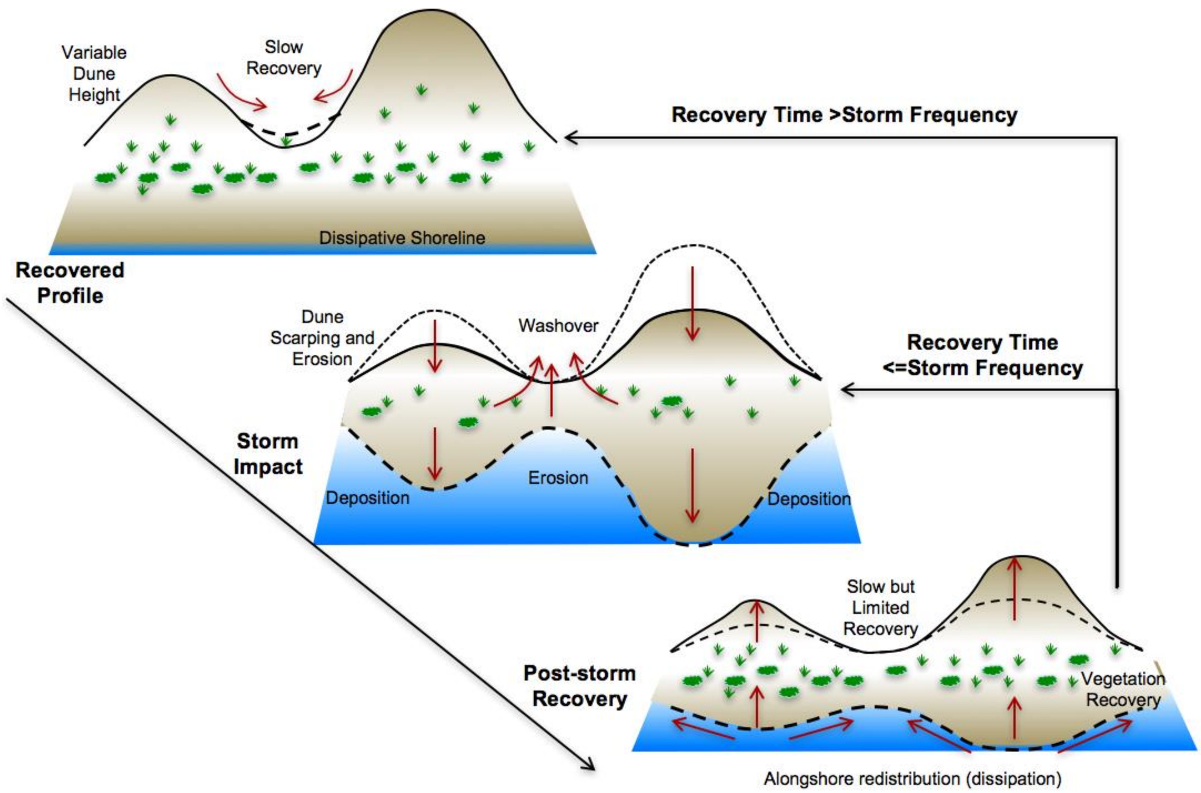

Variable
Dune
Height
Slow
Recovery
Recovery Time >Storm Frequency
Dissipative Shoreline
Recovered
Profile
Dune
Scarping and
Erosion
Washover
Recovery Time
<=Storm Frequency
Storm
Impact
Erosion
Deposition
Deposition
Slow but
Limited
Recovery
Post-storm
Recovery
Vegetation
Recovery
Alongshore redistribution (dissipation)

Figure 11

Highlights

- Scale dependent relationship between shoreline change and dune height
- Historical shoreline retreat increases with greater dune variability
- Dune variability is an important control on barrier island transgression
- Anthropogenic disturbance can enhance dune variability and rate of shoreline retreat
- Dune variability reinforced by scarping and washover during storms